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4D Dynamic RNP Annual Interim Report—Year 1

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1 Introduction

Joint Program Development Office (JPDO)Concepts of Operations for the Next Generation Air Transportation System (NextGen) considers 4 Dimension Trajectory (4DT) procedures a key enabler to Trajectory Based Operations (TBO). The JPDO defines 4DT as "a precise description of an aircraft path in space and time". While NextGen assumes that this path is defined within an Earth-reference frame, many 4DT procedure implementations will require an aircraft to precisely navigate relative to a moving reference such as another aircraft to form aggregate flows or a weather cell to allow for flows to shift. Current methods of implementing routes and flight paths rely on aircraft meeting a Required Navigation Performance (RNP) specification and being equipped with a monitoring and alerting capability to annunciate when the aircraft system is unable to meet the performance specification required for the operation. Since all aircraft today operate within the NAS relative to fixed reference points, the current RNP definition is deemed satisfactory. However, it is not well understood how the current RNP construct will support NextGen 4DT procedures where aircraft operate relative to each other or to other dynamic frames of reference. The objective of this research effort is to analyze candidate 4DT procedures from both an Air Navigation Service Provider (ANSP) and aircraft perspective, to identify their specific navigational requirements, assess the shortcomings of the current RNP construct to meet these requirements, to propose an extended 4 Dimensional Dynamic RNP (4D Dynamic RNP) construct that accounts for the dynamic spatial and temporal nature of the selected 4DT procedures, and finally, to design an experiment using the Airspace and Traffic Operations Simulation (ATOS) system to validate the 4D Dynamic RNP construct.

This Annual Interim Report summarizes the activities led by Raytheon, in collaboration with GE Aviation and SAIC, and presents the results obtained during the first year of this research effort to expand the RNP concept to 4 dimensions relative to a dynamic frame of reference. A comprehensive assessment of the state-of-the-art international implementation of current RNP was completed and presented in the Contractor Report "RNP State-of-the-Art Assessment, Version 4, 17 December 2008". The team defined in detail two 4DT operations, Airborne Precision Spacing and Self-Separation, that are ideally suited to be supported by 4D Dynamic RNP and developed their respective conceptual frameworks, "Required Interval Management Performance (RIMP) Version 1.1, 13 April 2009" and "Required Self Separation Performance (RSSP) Version 1.1, 13 April 2009". Finally, the team started the development of a mathematical model and simulation tool for RIMP and RSSP scheduled to be delivered during the second year of this research effort.

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2 Technical Approach

The Raytheon team brings a broad and comprehensive perspective on RNP and Trajectory Based Operations including operational support to the FAA for the implementation of Area Navigation (RNAV) and RNP, implementation of advanced 4D capable avionics for airframe manufacturers and operational support to operators, modeling and simulation development of advanced CNS capabilities into ATOS, and support of various experiments for the NextGen Airspace Project. While our technical approach attempts to use and build upon the content and document structure of the Minimum Aviation System Performance Standards (MASPS, DO-236B) and Minimum Operational Performance Specifications (MOPS, DO-283A) developed by RTCA, we have leveraged the team's breadth of perspective and expertise to determine the practicability of extending this construct to 4D RNP relative to a dynamic frame of reference.

For Year 1 of this research effort, the key elements of our technical approach were:

1. Assessment of international state-of-the-art in 2D, 3D and 4D RNP capability and use of RNP procedures and performance levels
2. Selection of candidate NextGen procedures and applications, and definition of the relevant 4D Dynamic RNP requirements
3. Develop a mathematical construct and implement a model for 4D Dynamic RNP in support of the selected procedures

3 RNP State-of-the-Art Assessment

The "RNP State-of-the-Art Assessment, v4, 17 December 2008" retraces the concept of Performance Based Navigation (PBN) from its origin in the early nineties and the development of satellite based technologies to the latest implementations throughout the world. The report documents the conceptual and operational perspectives of lateral, vertical, and time Required Navigation Performance. It also provides a directory of the documents related to PBN/RNAV/RNP, the RNAV and RNP Procedures and a status of international RNP implementation.

4 4D Dynamic RNP Overview

4.1 Introduction

RTCA document DO 236B contains MASPS for RNAV systems operating in an RNP environment. This report will start with DO-236B requirements and apply them to developing performance requirements for aircraft self-separation and self-spacing applications.

The Next Generation Air Transportation System (NextGen) is envisioned as a revolutionary transformation of the U.S. airspace to a performance-based, scalable, network enabled system that will be flexible enough to meet future air traffic needs. One of the major transformations is the use of TBO as the main mechanism for managing traffic at high density or in highly-complex airspace. These TBOs will be specified between the user and the air navigation service provider

(ANSP) and agreed in a "contract", using advanced automation. Overall, preferences for all users are accommodated to the greatest extent possible, and trajectories constrained only to the extent required to accommodate congestion, or for security, safety or environmental reasons. Changes to that "contract" will be made collaboratively, balancing the user preferences with the ANSP constraints.

A major element of TBO is trajectory-based separation management (SM), which uses automation and shared trajectories to better manage separation among aircraft and airspace and hazards such as weather and terrain. TBO provides a means for maintaining a target level of safety (TLS) while increasing traffic densities well beyond what is possible today given the workload, uncertainty, and execution delays inherent in current ground-based air traffic management.

5 Required Self Separation Performance

5.1 Introduction

This section examines what would be required in order to ensure a TLS for a scenario, in which aircraft have primary responsibility for providing separation from other aircraft in contrast to the current system where that responsibility lies with the ground-based ANSP. It describes the system components, identifies key system parameters, and derives an RNP-like construct for self-separation operations.

5.1.1 Separation Background

Separation is the term used to describe the act of keeping aircraft at such distances from each other that the risk of their colliding with each other is below a TLS. Such separation distances are specified as horizontal or vertical standards. Separation in the horizontal plane can be applied either longitudinally, spacing aircraft behind each other; laterally, spacing aircraft side by side; or a composite of the two, providing separation for aircraft whose paths cross. When not horizontally separated, vertical separation is achieved by aircraft operating at different altitudes (flight levels). The required separation is usually expressed in terms of minimum distances in each dimension, which should not be infringed. In the case of horizontal separation, the minimum distance can be expressed in either nautical miles, degrees of angular displacement (e.g.: on departure) or, in the longitudinal dimension, as either time-based or distance-based minima.

The separation minima used by Air Traffic Services (ATS) today in radar-controlled airspace takes into account that any decisions are based on a picture of the airspace derived from radar surveillance. The separation minima used must therefore ensure that even in the worst case surveillance conditions the positive separation of aircraft can be maintained. The implementation of Automatic Dependent Surveillance (ADS) and digital data link communications technologies into the NAS will provide significant improvements beyond current procedural ground-based control. This is due to the increased frequency and accuracy of position updates as well as information on the future intent of the aircraft. The technology should enable significant reductions in separation and spacing minima.

5.1.2 Enabling Technologies: RNP and ADS-B

Figure 1-1, “Navigation System Block Diagram”, from DO-236B provides a general description of the functions and describes the relationship between the various elements of the navigation system. One of the elements critical to precision separation is the path definition function since it computes the defined path to be flown in relation to the vertical, horizontal, and time dimensions. The RNP concept provides the means for quantifying lateral containment integrity and containment continuity, both of which are needed in order to demonstrate a TLS for TBO.

Unfortunately, DO-236B only discusses, in detail, lateral path definition whereas NextGen envisions TBOs based on full 4DTs. Two dimensional trajectory (2DT) operations are defined by longitudinal and lateral positions and define a ground track. Three dimensional trajectories (3DT) add the vertical position so that altitude is defined anywhere along the ground track. 4DT adds the time element to trajectory-based operations.

Full 4D TBO will require updated equipment standards and aircraft capabilities:

- **a.** Navigation and Guidance - more precise definition of vertical profiles and better definition and precision for along track/time-control,
- **b.** Communication – ability to describe trajectory windows and performance in all dimensions and to access available data and negotiate trajectories,
- **c.** Surveillance – ability to conduct relative navigation (spacing) or accept delegated separation, and finally
- **d.** Flight Crew Displays and Decision Support – flight crew awareness and management of TBO.

This report assumes the use of a surveillance technology with the full capabilities defined for Automatic Dependent Surveillance – Broadcast (ADS-B) systems defined in DO-242A to provide aircraft with position, velocity, and identification data about the aircraft operating in their vicinity, and in some instances, more complete intent information than is currently defined in the published ADS-B standards.

5.2 System Overview

A key new technology required to support self-separation is an Airborne Separation Assistance System (ASAS). This system is needed to monitor the state and intent of the ownship aircraft in the context of the state and intent of reference aircraft as determined by the onboard surveillance function. The ASAS is expected to not only alert the flight crew to predicted losses of separation (conflicts), but also to supply one or more maneuvers that, if implemented, should resolve such conflict(s). The relationship of the ASAS to other aircraft systems is depicted in Figure 1.

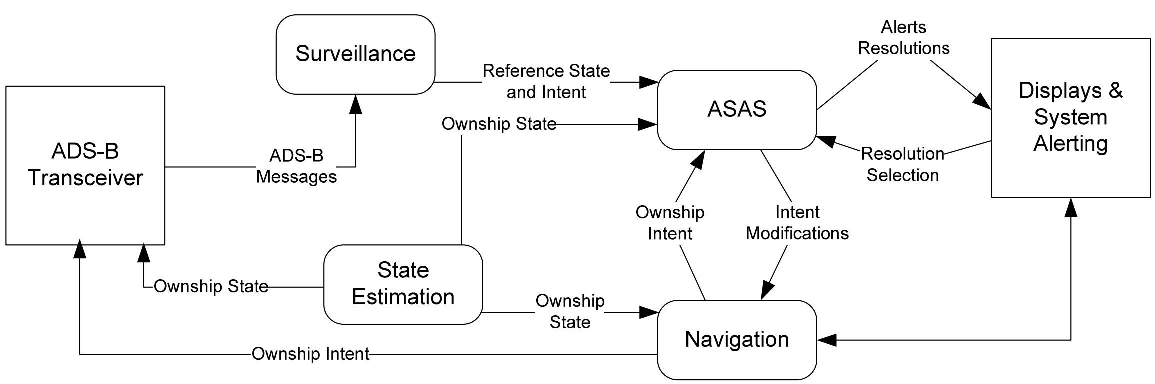

Figure 1 - Separation System Functional Block Diagram

5.2.1 ADS-B Transceiver

The ADS-B transceiver transmits and receives ADS-B signals. It collects outgoing data from the position estimation and navigation functions. Received ADS-B messages are passed to the Surveillance function for processing.

5.2.2 Surveillance

The Surveillance function assembles ADS-B messages and maintains target and track information for each aircraft within ADS-B range. The Surveillance function is responsible for track initiation and maintenance and ensures that a consistent set of intent data for cooperating targets is available for the other aircraft functions.

5.2.3 State Estimation

The state estimation function maintains the estimate of the aircraft's position, velocity, and the current time. It provides estimates of the quality of the position and velocity data. This function also includes the real-time estimation of the local wind vector based on the difference between ground-referenced velocity and air-referenced velocity.

5.2.4 Navigation

The navigation function generates the expected 4D trajectory of the ownship aircraft (ownship intent). This trajectory is updated in accordance with changes generated by the pilot or when the aircraft state deviates from the trajectory in dimensions that are not being controlled (e.g. time drift when there is not RTA constraint). The navigation function also provides the guidance signals to the flight control system and to the flight crew.

5.2.5 ASAS

The ASAS function compares the aircraft state and trajectory to the estimated state and trajectory of reference aircraft to monitor predicted separation, detect potential conflicts, and provide conflict resolution guidance in order to ensure that safe separation will be maintained. The estimated trajectory of reference aircraft is based either on broadcast intent information (Class A systems) or projection of state information in the absence of reference intent. When a loss of separation is projected within a specified time horizon, the ASAS function presents an indication to the flight crew and computes one or more resolution maneuvers for pilot selection and execution.

5.2.6 Display and System Alerting

This function encompasses the interfaces between the aircraft systems and the flight crew.

5.3 Required Self-Separation Performance

Analogous to the different performance levels used to define RNP capabilities and airspace user requirements, a suitable performance characterization, Required Self-Separation Performance (RSSP), is needed for ASAS equipped aircraft. The expectation is that an RSSP performance level will define a sufficient set of system performance attributes to permit determination of the separation buffer required to attain a specified TLS. Unlike RNP, the RSSP will need to be

based on a multi-dimensional set of metrics in order to encompass the main interdependent parameters that affect achieving the target level of safety[1] (TLS) for a given traffic density/complexity (or, conversely, the traffic density/complexity for which a given TLS can be sustained)[2]. These interdependent parameters include:

a) Aircraft navigation and guidance performance (4D RNP);
b) Surveillance performance (range, accuracy, update rate/latency, update reliability, level of intent detail, and level of intent accuracy which has not yet been defined);
c) Conflict resolution algorithm capabilities (how boxed in does the ownship need to get before no resolution can be found); and
d) Look ahead time horizon (how far ahead are conflicts typically detected and resolution maneuvers reflected in intent broadcasts).

The expectation is that controlling these parameters will permit progressively reducing separation standards by reducing uncertainty and unpredictability in the overall system, thereby permitting higher-performing aircraft to operate in higher density airspace. These parameters are interdependent in that an increase or decrease in any single parameter may result in a corresponding increase or decrease in some or all of the others. RSSP is a consolidation of RNP, Required Communications Performance (RCP) of the surveillance datalink, and Required Surveillance Performance (RSP)[3]. RSSP is effectively a Communications, Navigation, and Surveillance (CNS)/ATM matrix where the outcome is directly related to a level of capability that is required to operate in a particular airspace.

5.3.1 Separation System Categories

This document recognizes two distinct classes of self-separation system. Class B systems use only position and velocity surveillance data (state data) from the reference aircraft in order to detect conflicts and determine separation maneuvers. Class A systems use not only the state data of class B systems, but also provide and receive intent data as part of the surveillance data exchange. Having this intent data greatly reduces the errors and uncertainties associated with linearly projecting state data into the future and permits Class A systems to make more accurate predictions further into the future than Class B systems and to account for planned maneuvers of other aircraft. The two classes are distinguished because the presence or absence of intent data has a significant impact on the analysis of separation errors.

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[1] TLS = the requisite Target Level of Safety for the airspace domain, e.g. Where, "fatal accidents per flight hour" is considered to be an appropriate metric, a TLS of $5x10^{-9}$ fatal accidents per flight hour per dimension for the en-route domain. NOTE: Where fatal accidents per flight hour is not considered to be an appropriate metric, justifiable alternative metrics and methods of assessment providing an acceptable TLS may be established. United States TERPS criteria provide an example for obstacle clearance at 10^{-7} per approach or 10^{-9} instantaneous collision from an obstacle.

[2] The numeric determination of a level of safety will depend upon the traffic density/complexity because the traffic density/complexity is a primary driver of conflict probability and the likelihood of finding conflict-free airspace to use for a conflict resolution.

[3] Definitions and standards for RCP and RSP are in development. The concepts of RCP and RSP have been discussed at ICAO. The FAA Associate Administrator for Safety talked about RCP, RSP and Required Total System Performance (RTSP) at the New technologies workshop in January 2007. Both are discussed in the NextGen Conops.

5.3.2 RSSP Concept

The accuracy, integrity, and continuity concepts for longitudinal/time performance (and vertical performance) has not been addressed by ICAO or FAA to the level of detail that RNP (lateral) has, and the MASPS address accuracy requirements of Estimated Time of arrival (ETA), Time of Arrival Control (TOAC), and Vertical Navigation (VNAV) only at a very high level. Currently, the standards only address performance relative to a fixed, earth-referenced path and do not in any way address performance measurement in a dynamic frame of reference, such as flight relative to another aircraft. Because of the need to be able to quantify a level of safety associated with self-separation operations, this document develops a proposed RSSP concept and associated requirements.

For consistency with the ICAO definition of RNP, the document defines RSSP as: A statement of the self-separation performance accuracy, integrity, continuity, and availability necessary for conducting self-separation operations within self-separation permissible airspace[4].

5.3.3 Application of RSSP

The term RSSP is applied as a descriptor for airspace where self-separation is permitted. This could encompass a large area, such as one or more en route or oceanic sectors, or to a more constrained volume such as a flow corridor as defined in the NextGen Concept of Operations (ConOps).

5.3.4 RSSP Types

The term RSSP -x-y is introduced to denote both an area of self-separation permitted airspace and, simultaneously, the minimum aircraft system performance required to perform self-separation within that airspace.

The ‘x’ indicates the class of RSSP system. Currently, two classes are defined:

- Class A systems provide and use both state and detailed intent information.
- Class B systems need only provide and use state information.

The ‘y’ indicates the category of required system performance. Each such category is associated with performance metrics that, taken together, define an aircraft’s ability to identify and resolve conflicts to a particular standard. The set of metrics is enumerated in Section 5.4.4. The definition of the specific categories and the metric thresholds associated with them, however, is beyond the scope of this document.

5.4 Operational Goals and Applications

Under a performance-based system, as envisioned by NextGen, excess separation resulting from today’s control imprecision (a product of available data and controller workload) and lack of

[4] While self-separation is only expected to take place in RSSP designated airspace, this statement does not imply that such airspace may not also contain aircraft for whom separation assurance is being provided for by the ANSP. This report does not address such ‘mixed’ operations or the related equipage requirements for non-RSSP aircraft that would result if RSSP aircraft are required to maintain separation from the non-RSSP aircraft.

predictability are minimized which enables reduced separation among aircraft. Also, separation management responsibility may be delegated or transferred to aircraft having the capability to perform that function. Self separating aircraft, as envisioned by NextGen, are required to maintain separation from all other aircraft, and obstacles and hazards, in the airspace. Aircraft follow the proper separation procedures and avoid any maneuvers that generate immediate conflicts with any other aircraft. Self separation procedures are conducted only in self separation airspace. Eventually, self separating aircraft will have 4 dimensional trajectories (4DT). Either the separation maneuver will leave the aircraft within the constraints of its 4DT, or the flight crew will need to negotiate a new 4DT. This document does not attempt to define a complete concept of operations for self-separation, and in particular, does not address issues such as the unambiguous handoff of separation responsibility when transitioning into and out of self-separation airspace.

5.4.1 Overview

The self-separation scenario looks at the situation when one aircraft (ownship) must pass no closer than a specified separation distance (or more generally, an exclusion zone)[5] from another aircraft (reference)[6]. In order to perform this maneuver reliably, ownship must target a separation that includes some extra buffer in addition to the required separation to account for uncertainties in ownship and reference aircraft state estimation and performance. Because this additional buffer represents inefficiency in the operation (use of airspace, excess ownship maneuvering, etc.), it is desirable to keep it to the practical minimum. The necessary size of this additional buffer, however, is a complex function of the uncertainties inherent in the measurement of the ownship and reference aircraft state, knowledge of reference aircraft intent (future maneuvers before reaching the point of closest approach), crossing geometry, and predictions of future aircraft positions based on current measurements. The necessary buffer size is also a function of the ownship ability to execute the required maneuvers accurately and in a timely fashion. The goal of this analysis is to be able to specify a mathematical construct, analogous to RNP in the cross-track direction, that can be used for determining the size of buffer required to produce a given level of assurance that ownship will not pass within the exclusion zone of reference (or cause reference to pass through ownship's exclusion zone) in the lateral and/or vertical dimensions[7], though for the purposes of this analysis, the focus will be on lateral separation.

5.4.2 Concept of Operation

The scenario assumes that at some point in time T_0, ownship determines (via ATC instruction, automation, or pilot) that it must maneuver to miss reference (i.e. be outside of the exclusion zone at the point of closest approach (PCA) to the boundary of the exclusion zone) by at least a

[5] This separation distance or exclusion zone must at a minimum account for the physical extent of each aircraft plus the wake vortex avoidance area behind each (not only must ownship not pass through reference's wake before it has decayed sufficiently, ownship must also not make reference pass through ownship's wake). If mitigation strategies are relied upon to account for excess uncertainty, mitigation will add to the separation distance.

[6] Or, in the general case, a non-stationary constraint such as a convective weather cell.

[7] This level of assurance is an element, along with alerting and mitigation strategies, of the analysis required to demonstrate a TLS.

specified distance, Figure 2.[8] The determination of which aircraft must maneuver is expected to be based on a set of rules, analogous to the *International Regulations for Preventing Collisions at Sea* and applied without the need for explicit coordination between aircraft.

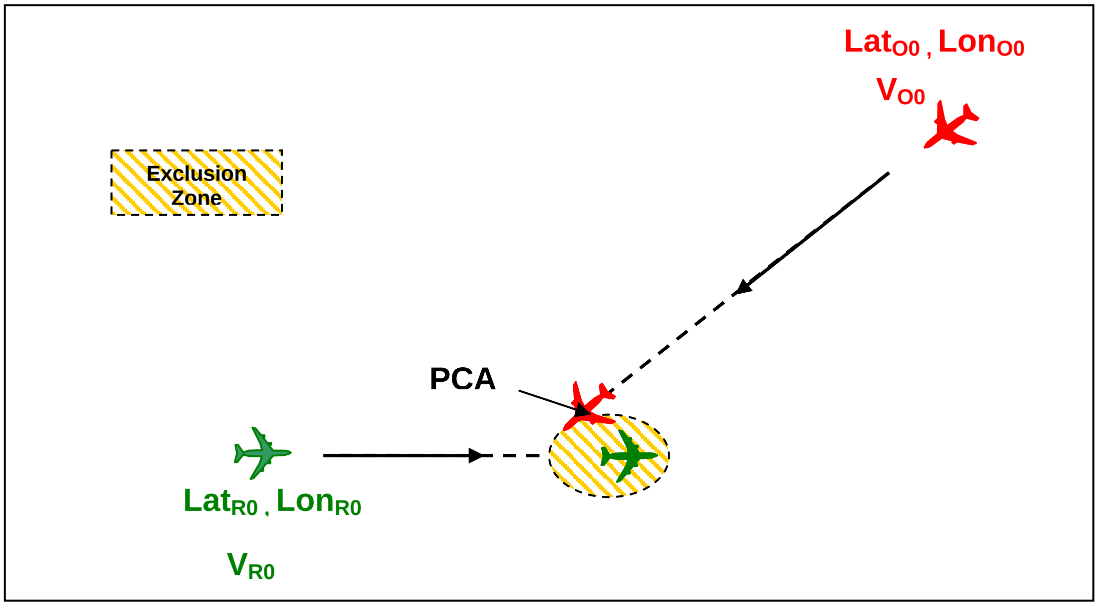

Figure 2 - Original Estimated Geometry

At T_0, ownship has an estimate of the position and velocity of both ownship and reference. Ownship may also have an estimate of the future trajectory of ownship and reference (intent information). In the horizontal plane, the maneuver could consist of a change of speed, as shown in Figure 3, or direction, as shown in Figure 4. Of course, a combination of these, or a change of altitude are also possible resolution maneuvers.

[8] While many of the errors and uncertainties considered in this analysis pertain to the accuracy of this determination, the focus will be on the post-maneuver portion of the case in order to include the contribution of maneuver uncertainty to the total.

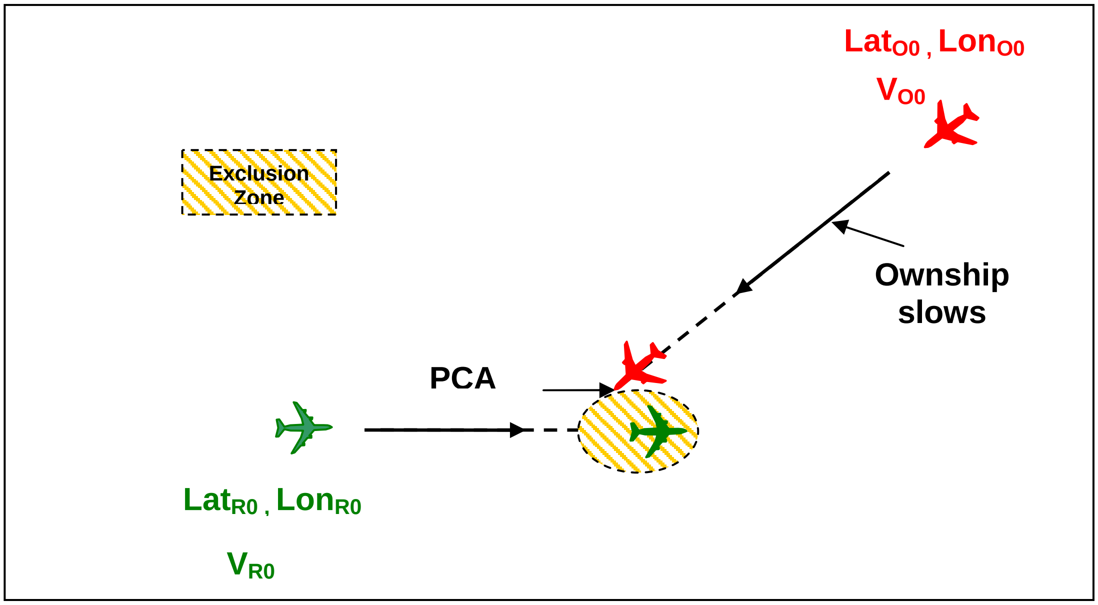

Figure 3 - Estimated Geometry after Ownship Slows

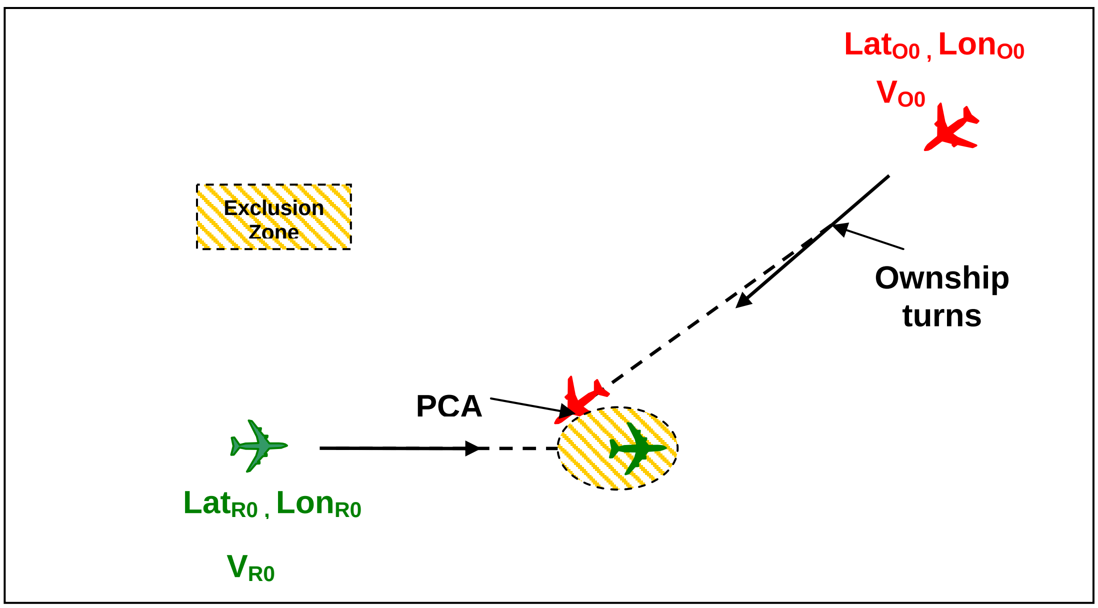

Figure 4 - Estimated Geometry after Ownship Turns

The scenario assumes that ownship has measurements of relevant state parameters and their accuracy and integrity from the onboard navigation system. It also assumes that ownship has some measurement of reference's state parameters and their accuracy and integrity via ADS-B transmissions from reference received by ownship's ADS-B receiver. For Class A systems, the scenario also assumes that some level of reference aircraft intent information is available, for example by ADS-B transmission of one or more Trajectory Change Points (TCPs), but the extent of that information will be kept as a parameter in the mathematical construct. The extent to which reference is permitted to maneuver without broadcasting intent adds directly to the uncertainty of the predicted separation and is outside the scope of this document. The analysis

will also assume that ownship has measurements of wind and other relevant atmospheric parameters as well as knowledge of the accuracy and integrity of those measurements.

5.4.3 Procedure Description

How responsibility for maintaining the minimum separation is transferred from ATC to ownship is immaterial to this analysis and will not be considered as part of the procedure. It is sufficient to begin with the premise that ownship has this responsibility. Furthermore, barring the introduction of new constraints, this procedure assumes that ownship will execute the maneuver(s) determined after T_0 without further alteration to compensate for error accumulation, so the maneuver(s) must include an adequate separation buffer[9].

5.4.3.1 Timeline/Decomposition of Events

- T_0 Ownship systems determine that a maneuver will be required to assure maintenance of the specified separation and inform the pilot.
- T_1 Ownship automation determines one or more candidate maneuvers that will assure maintenance of the specified separation and present them to the pilot.[10]
- T_2 Ownship pilot selects which maneuver candidate will be executed.
- T_3 Ownship pilot configures onboard navigation system to perform the selected maneuver sequence.
- T_4 Ownship ADS-B begins broadcasting new intent information (Class A systems).
- T_5 Ownship executes planned maneuver(s).
- T_6 Ownship passes Point of Closest Approach (PCA) to reference, which, if the buffer used was adequate, meets or exceeds the specified separation distance.

5.4.3.2 Pilot Procedures

The ownship pilot is assumed to have already accepted responsibility for maintaining separation from reference before the scenario begins. Within the scenario, the pilot is responsible for:

1. Selecting the preferred separation maneuver(s),
2. Configuring the navigation system to perform the selected maneuver(s),
3. Ensuring that ownship performs the selected maneuver(s), and
4. Monitoring to ensure that the maneuver provides at least the specified separation (this monitoring is aided by the onboard tools).

5.4.4 Errors and Uncertainties

The construct for determining the required separation performance needs to account for:

1. Accuracy and integrity of ownship state data.
2. Accuracy of ownship planned trajectory (both current and planned maneuver), which depends on:

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[9] This assumption/constraint is introduced in recognition of the cockpit workload implications of a strategy that continuously updates the maneuver based on the evolving state of the two aircraft.

[10] We assume that the tools leave sufficient time before the assumed initiation of each maneuver candidate to allow pilot selection and implementation to take place before the initiation time.

a. Control method accuracy (manual vs. automatic guidance)
b. Accuracy of modeling method (e.g. 6 DOF vs. kinematic) and modeling parameters (thrust, drag, etc).
c. Accuracy of predicted wind and temperature data.
d. Accuracy of earth model.
e. Correspondence between planned/predicted maneuver and actual maneuver executed (time of execution, acceleration/deceleration magnitude and transition, roll-in/roll-out transitions, turn-rate/bank angle used). This should directly correspond to 4D RNP performance level.

3. Accuracy and integrity of reference state data.
4. Accuracy and completeness of reference intent data (which depends on the same factors as the ownship data).
5. Encounter geometry (e.g. crossing angle).
6. ETE to point of closest approach in the resolution maneuver.
7. Anticipated ownship FTE bounds near point of closest approach.

The effects of these errors are represented in Figure 5. Note that it is expected that the total uncertainty will increase the further into the future that the aircraft state is predicted. For Class A systems, this increase will be capped by the 4D RNP accuracy and containment associated with the ownship trajectory and reference aircraft intent. For Class B systems, this growth is a result of integrating velocity over time in order to make the predictions of future position. In practice, this growth may be exponential for the prediction of the reference aircraft's state because of the possibility of unannounced maneuvers by the reference aircraft.[11] For the purposes of performance evaluation, however, any such maneuvering would be considered to create a new encounter situation.

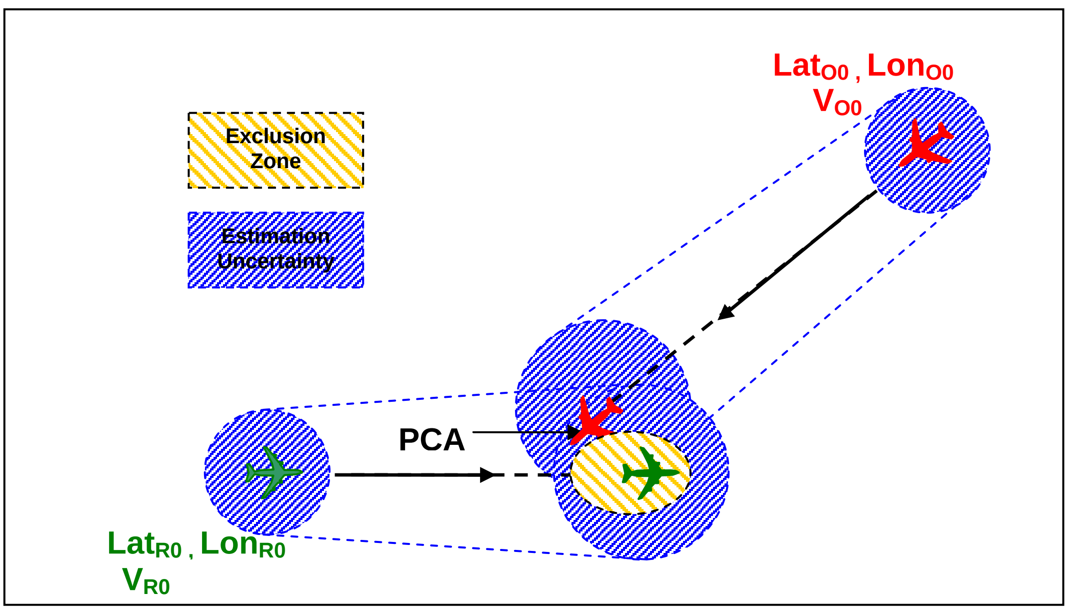

Figure 5 - Estimated Geometry with Uncertainties and Errors

[11] The expectation is that such maneuvers would be away from ownship, except in the case of near-simultaneous maneuvering.

The overall separation performance can be quantified by defining containment boundaries in the lateral and vertical dimension. These boundaries correspond to the region within which the actual separation will fall 95% of the time. They can also be used to define a further region that the actual separation will not exceed without alert with extremely high probability. Unlike in the case of RNP-RNAV, however, definition of the containment boundaries is not, in itself, adequate to be able to quantify a TLS. For RNP-RNAV, considerable freedom is left to the designer to make performance tradeoffs among the various system characteristics that contribute to overall lateral performance. For RSSP, however, there is a need to place additional constraints on this trade-space because the separation performance depends on the combined performance characteristics of two independent vehicles.

In order to ensure that any pair of vehicles conforming to a given RSSP performance level will yield the desired overall separation performance, additional vehicle error, uncertainty, and system characteristics must be constrained for a given RSSP performance level. These errors, uncertainties, and system characteristics are captured using the following metrics which will be further defined in Section 5.7.1:

a) 4D RNP performance level[12];
b) Accuracy, integrity and continuity of surveillance data from reference aircraft, including intent data if present;
c) How quickly the aircraft can respond (the relative time between recognizing that a conflict requires a resolution maneuver and completion of that resolution maneuver);
d) How long before closest point of approach conflict resolution maneuvers can be selected;
e) How long before initiation of non-emergency maneuvers new intent information is broadcast;
f) Surveillance system range at X% message reception probability and other surveillance datalink performance characteristics; and
g) Degrees of freedom employed for resolution maneuvers (lateral, longitudinal, vertical, and combinations thereof);

5.5 Assumptions

This document makes several assumptions applicable to all classes of system, and the remainder applies to Class A systems only.

5.5.1 Assumptions Applicable to All Classes

5.5.1.1 Uniformity of Equipage

Because the RSSP capability is expected to be applied to a volume of airspace, it is assumed that all aircraft operating in that airspace will at least meet the minimum RSSP standards required by the airspace.

[12] The 4D RNP performance level defines the accuracy, integrity, and continuity performance of each aircraft in the lateral (RNP-RNAV), longitudinal/time (TOAC), and vertical (VNAV) dimensions.

5.5.1.2 Reference Aircraft State

The RSSP concept assumes that all aircraft in the airspace continuously transmit and receive ADS-B data in compliance with RTCA DO-242A including the following parameters:

- Target identity
- Latitude and longitude
- Pressure altitude
- Position accuracy and integrity
- North and east velocity
- Vertical speed
- Velocity accuracy and integrity
- Time of applicability (reference time of the other state parameters)

It is further assumed that ownship and reference are either using the same transmission format for ADS-B (e.g. 1090ES or UAT) or the airspace is served by an Automatic Dependent Surveillance – Rebroadcast (ADS-R) service that reliably echoes messages between the two transmission formats with negligible delay.

5.5.1.3 Ownship State

The ASAS function has access to at least the set of ownship state parameters for that is available via ADS-B for the reference aircraft.

5.5.2 Assumptions Applicable to Class A Systems

5.5.2.1 Reference Aircraft Intent

The primary differentiator between Class A and Class B systems is the availability of intent information for the reference aircraft. The intent information, which is not yet fully defined in the relevant ADS-B standards, will at least describe the intended motion of reference as a sequence of segments within which intermediate 4D states may be computed without significant accuracy degradation using the assumption of uniform (possibly zero) acceleration along the three primary aircraft axes. This intent information should cover at least the minimum time horizon required by the applicable RSSP performance level for conflict detection. The intent information will be updated whenever the reference aircraft's current intent differs significantly relative to the accuracy requirements of the intent broadcast (which will in turn be specified either by the ADS-B standard or by the RSSP performance level). For RSSP performance levels intended for use in dense and complex airspace, there is a requirement that the reference aircraft broadcast a change in intent at least a minimum notification time in advance of performing a maneuver[13] that had not been included in prior intent broadcasts. This requirement is needed to reduce the likelihood of simultaneous conflicting near-term maneuvers.

5.5.2.2 Ownship Intent

The RSSP concept assumes that a Class A system has access to detailed and accurate ownship intent information and associated accuracy metrics from the onboard Flight Management System

[13] Obviously, this requirement would not apply to the non-normal case of a maneuver required for collision avoidance or other safety-related exigency.

(FMS) or equivalent. Ownship is assumed to be operating at a specified 4D RNP level (a successor to the current standard that defines containment in the longitudinal/time and vertical dimensions in addition to the lateral dimension) such that guidance is provided to maintain conformance to broadcast intent in all dimensions. Alternatively, ownship intent will be updated before significant deviations accumulate in the longitudinal/time or vertical dimensions.

5.6 Definitions

The definition of key terms used in this section is collected below for convenience. Italics are used to denote terms in these definitions that may be found in this section.

5.6.1 Required Self-Separation Performance

SELF-SEPARATION
The process by which one aircraft assumes responsibility for managing the distance between itself and one or more reference aircraft without direct involvement of the ANSP.

REQUIRED SELF-SEPARATION PERFORMANCE (RSSP)
A statement of the *self-separation* performance necessary for operation within a defined airspace.

CLASS
The type or category of RSSP compliant system.

CLASS A
An RSSP compliant system that uses intent information to provide more robust conflict detection and avoidance capabilities in airspace where aircraft can reasonably be expected to be maneuvering (e.g. terminal or high density airspace).

CLASS B
An RSSP compliant system that needs only position and velocity information to perform conflict detection and resolution.

EXCLUSION ZONE
The volume around an aircraft that no other aircraft may be permitted to transgress, either due to risk of physical contact or risk of significant wake vortex encounter.

POINT OF CLOSEST APPROACH (PCA)
The *3D position* where the lateral distance of one aircraft to the other aircraft's *exclusion zone* is at a minimum, or, in the vertical dimension, the *3D position* where the vertical distance of one aircraft to the other aircraft is at a minimum while either aircraft is within the lateral extent of the other aircraft's *exclusion zone*[14].

[14] The concept of exclusion zone is introduced to distinguish between pure metal-on-metal contact-based standards versus future standards that need to account for such things as wake vortices because of their reduced dimensions.

DESIRED SEPARATION
The required lateral (or vertical) distance, between Ownship and Reference Aircraft at the *PCA*.

DEFINED SEPARATION
The lateral (or vertical) distance, between Ownship and Reference Aircraft at the *PCA* that is input to the ASAS function.

ACTUAL SEPARATION
The true lateral (or vertical) distance, between Ownship and Reference Aircraft when they are at the true *PCA*.

ESTIMATED SEPARATION
The output of the separation computation function, equal to the computed lateral (or vertical) separation at the computed *PCA*. This does not take into account potential future maneuvers that are not reflected in the ownship *predicted trajectory* or the reference aircraft *intent.*

5.6.2 Trajectory

3D POSITION
A position in space consisting of latitude, longitude, and altitude.

TIME REFERENCE
The reference time source for the trajectory; for example, Universal Coordinated Time (UTC).

CURRENT TIME
The present time according to the *time reference*.

PREDICTED TRAJECTORY
The predicted *3D position* of an aircraft as a function of time.

INTENT
The representation of an aircraft's *predicted trajectory* that is encoded in ADS-B messages.

ESTIMATED TIME
The time input to the trajectory prediction function, synchronized to the *time reference*.

ESTIMATED 3D POSITION
The *3D position* input to the trajectory prediction function. This position is determined by a Navigation function based on sensor inputs.

ESTIMATED TIME OF ARRIVAL (ETA)
The time at which an aircraft will arrive at a defined point on the *predicted trajectory*.

TIME TO GO (TTG)
The duration from the *current time* until the aircraft reaches a defined point, typically in this discussion, the *PCA*.

TRAJECTORY CHANGE POINT (TCP)
A discrete point on the *predicted trajectory* containing the latitude, longitude, altitude, time, and speed (either CAS or Mach). This is a basic set of variables that may be standardized and/or expanded in the future.

5.6.3 Error Terms

SEPARATION ERROR
The difference between the planned separation at the *PCA* when a clearance maneuver was formulated and the separation at the actual *PCA*. The tails of the statistical distribution of this parameter are effectively bounded for each combination of RSSP class and performance level and conflict encounter geometry (crossing angle and speeds).

LATERAL SEPARATION ERROR
The separation error measured in the horizontal plane.

SEPARATION DEFINITION ERROR (SDE)
The difference between the *desired separation* and the *defined separation*, for example due to approximations used in the separation function to define the *exclusion zone*.

ESTIMATED TIME ERROR (ETE)
The difference between the *current time* and the *estimated time*, synchronized to the *time reference*.

ESTIMATED POSITION ERROR (EPE)
The difference between the true *3D position* and the *estimated 3D position* of the aircraft.

COMPUTED SEPARATION ERROR (CSE)
The difference between the *estimated separation* and the *defined separation*.

SEPARATION ESTIMATION ERROR (SEE)
The error in the computation of *estimated separation.*

SEPARATION CONTROL AUTHORITY (SCA)
The ability of ownship to maneuver in order to compensate for *computed separation error* and *separation estimation error.*

TOTAL SEPARATION ERROR (TSE)
The difference between the *actual separation* and the *desired separation.* It is equal to the sum of the *separation definition error, computed separation error,* and *separation estimation error* less the *separation control authority.* The *separation control authority* is subtracted because it

represents a controllable portion of the error. The uncontrollable portion of the error is analogous to the FTE in RNP.

5.6.4 Separation Containment Concept

The concept of separation containment is based on the concept of lateral (or cross-track) containment as defined in RTCA DO-236B, but the manner in which it is measured differs. For RSSP, the "RNP value" used in RNP-RNAV is replaced with a pair of measures, Separation Boundary Lateral (SBL) and Separation Boundary Vertical (SBV). This pair of measures defines limits, in the lateral and vertical dimensions respectively, around the *desired separation* within which the *actual separation* will fall for at least 95% of encounters requiring some form of resolution maneuver.

Separation containment integrity requirements limit the probability of the *Total Separation Error* exceeding the SBL/SBV requirements with no annunciation at least some specified time T before reaching the *PCA*.

Separation containment continuity requirements limit the probability of a loss of function. In this context, function is defined as the ability to meet the separation containment requirement (i.e. to be within the desired SBL/SBV limits at and after time T).

There are five possible system states relative to the SBL/SBV limits. These states are:

1) S1: TSE > SBL/SBV, TTG > T, no alert (Integrity)
2) S2: TTG > T, alert (Continuity)
3) S3: TSE > SBL/SBV, TTG < T, no alert (Integrity)
4) S4: TTG < T, alert (Continuity)
5) S5: TSE < SBL/SBV, no alert (Normal Operations)

Note: P(S1) + P(S2) + P(S3) + P(S4) + P(S5) = 1 where P(x) is the probability of the system being in State x.

T is the minimum amount of time prior to reaching *PCA* that the alert must be made if the aircraft cannot achieve the *desired separation*.

States 1 and 3 represent the set of events associated with a loss of separation performance with no annunciation (alert), and are thus the **integrity requirements**. The uncertainties associated with separation predictions generally increase with time or distance from the current position (primarily due to forecast wind uncertainties). Thus, the probability of State 1 will be greater than the probability of State 3 (P(S1) >> P(S3)) due to TTG being > T. However, it also needs to be considered that the control authority that ownship has to correct for these uncertainties will also generally decrease as the aircraft approaches the *PCA*. This needs to be considered when determining a prior time T beyond which it is critical that an annunciation be received. Thus, the

probability of S1 must be less than XX[15] per flight hour, while the probability of S3 must be less than YY per operation.

The **continuity requirement** applies to states S2 and S4 where the loss of function is detected and annunciated. When current time is still far before T, the available control authority will be larger, and thus the probability of state S2 must be less than WW per flight hour. When the aircraft is close to time T the control authority is greatly reduced, and thus the probability of S4 must be less than ZZ per flight hour. S5 represents the normal operation where the error is less than the SBL/SBV.

In addition to the containment requirements, there is an **uncertainty parameter** associated with the predicted separation. This uncertainty must be bounded to ensure appropriate control authority is available.

CONTAINMENT
A set of interrelated parameters used to define the performance of a separation control system. These parameters are *containment integrity* and *containment continuity.*

CONTAINMENT INTEGRITY
A measure of confidence in the estimate, expressed as the probability that the system will detect and annunciate the condition where the TSE is greater than the SBL/SBV limit and the condition has not been detected.

CONTAINMENT CONTINUITY
The capability of the total system to satisfy the performance limit without nonscheduled interruptions during the intended operation. Nonscheduled interruption is defined to be either 1) total loss of time prediction capability; 2) a failure of the system which is annunciated as a loss of time performance capability; or 3) a false annunciation of loss of time performance capability.

CONTAINMENT REGION
A region in both the along-track and cross-track dimensions, centered on the *desired along track position* on the *desired path* at a desired time T, to which the *containment integrity* and *containment continuity* are referenced.

SEPARATION BOUNDARY LATERAL (SBL)
The limit in the lateral dimension around the *desired separation* within which the *actual separation* will fall for at least 95% of encounters requiring some form of resolution maneuver.

SEPARATION BOUNDARY VERTICAL (SBV)
The limit in the vertical dimension around the *desired separation* within which the *actual separation* will fall for at least 95% of encounters requiring some form of resolution maneuver.

[15] This and the following probability parameters will need to be determined based on a TLS and any mitigations that are identified as part of the procedures defined by the ANSP. In practice, they will likely be tailored to specific RSSP performance categories.

5.7 System Performance Requirements

5.7.1 Accuracy

Accuracy is a measure of the difference between an aircraft's intended separation from a reference aircraft at the PCA (relative to the exclusion zone boundary) and the true separation at the true PCA. It is given by a value associated with a confidence interval. For example; within airspace requiring a particular RSSP performance level, the separation error will not be greater than 0.5 nautical miles for 95% of the conflicts requiring a resolution maneuver.

5.7.2 State Data Accuracy Metrics

5.7.2.1 The first two metrics deal with the accuracy of navigation data available to ownship and of the surveillance data provided by reference (and by inference, provided by ownship). Ownship Navigation Accuracy

If ownship is operating according to 4D RNP standards, then those standards define the lateral and longitudinal accuracy and containment parameters for ownship state estimation both at the present position and along ownship's 4D trajectory. This is the expected norm for Class A systems. For Class B systems, it will be necessary to break this metric into individual lateral position, longitudinal position, and velocity sub-metrics in order to specify the ownship navigation accuracy.

5.7.2.2 Reference Surveillance Accuracy

The position and velocity accuracy and integrity for the reference accuracy are reported in ADS-B messages as the navigation accuracy for position and velocity plus the surveillance integrity level. When intent data is broadcast, it will need similar reported metrics. For a given RSSP performance level, a set of minimum acceptable values for each of these quality metrics will constitute the reference surveillance accuracy metric.

5.7.3 Additional Metrics

In order to characterize the ability of an aircraft to perform self-separation, especially in more congested airspace, additional metrics also need to be specified.

5.7.3.1 Response Time

This metric measures how quickly the aircraft can respond to the need to resolve a conflict. This applies whether the time to go to an anticipated conflict has just reached a threshold value or the reference aircraft has either maneuvered or broadcast new intent. It is measured as the relative time between recognizing that a conflict requires a resolution maneuver and completion of that resolution maneuver.

5.7.3.2 Look Ahead

Look ahead measures how long before the closest point of approach a conflict resolution maneuvers can be selected. It is primarily dictated by the accuracy of separation prediction as a

function of time to go to PCA and the characteristics of the surveillance datalink (reception probability versus range).

5.7.3.3 Intended Maneuver Anticipation Time

For Class A systems, it is expected that the ASAS function will plan the resolution maneuver to commence some time in the future in order to provide notice of the change in intent to neighboring aircraft before the maneuver begins. This metric captures the amount of time before the initiation of non-emergency maneuvers that new intent information is broadcast.

5.7.3.4 Surveillance Datalink Performance

In order to function effectively, the ASAS function needs to have surveillance data at a range that exceeds its required look ahead time. Given assumptions of maximum closing speeds expected in a particular class of airspace, this can be translated into a surveillance range requirement defined as the range at which there is at least an X% (X >= 95) probability of receiving each transmission from reference.

5.7.3.5 Resolution Flexibility

Lower performance category ASAS systems might only provide simple lateral maneuvers, such as turns or sidesteps, to resolve conflicts. Higher performance systems would take advantage of lateral, vertical, and speed controls to find resolutions. The highest performing systems might be able to plan complex combinations of the three and be able to find resolution paths in the presence of multiple potentially conflicting aircraft. This metric seeks to enumerate or quantify these differing performance levels. Looked at another way, this metric captures the robustness with which the ASAS can find a path through multiple constraints.

5.8 Integrity

Integrity is a measure of the probability that information provided by a system will not be hazardously misleading. It is generally expressed as a probability of occurrence per operating hour, which expresses likelihood that a system will send the user bad/incorrect information that could cause a potentially dangerous situation without a timely warning. For example the likelihood that the separation error exceeds a maximum of 1.0 nautical miles, without having alerted the flight crew at least 90 seconds in advance of the exceedance, shall be less than 10^{-5} per flight hour.

5.9 Continuity

Continuity is the capability of a total system to perform its intended function without a non-scheduled interruption during the intended operation assuming the system was available when the procedure was initiated. Continuity is expressed per unit of time. For example; the calculations of a single thread transponder mean time to failure of 5,000 hours.

5.10 Availability

Availability is the probability that a system will perform its required function at the initiation of the intended operation. For example, the FAA target for availability of the Wide Area Augmentation System is 0.999.

6 Required Interval Management Performance

6.1 Introduction

Airborne Precision Spacing (APS) has been developed by NASA as an element of pair-wise interval management to improve the merging and spacing performance during approach and landing for high-density operations. APS provides speed control guidance to the flight crew with an assigned spacing interval in the time domain at the runway threshold or a common waypoint with respect to a paired leading airplane (reference aircraft). Speed control guidance is derived from both the reference aircraft and ownship's flight profiles, current states of the reference aircraft and the ownship, and speed and altitude constraints at intermediate points along the approach routes. The projected benefits of APS include providing the flight crew and air traffic controllers an automated speed control tool and advisories in delivering airplanes at the runway threshold at precise time intervals. This precise performance can optimize the flow of traffic approaching the runway, and may increase the runway throughput [1]. The concept of APS is also in full conformance with two key NextGen environment components as defined by Joint Planning and Development Office (JPDO) [2], which are Performance-Based Operations and Services and Aircraft Trajectory-Based Operations (TBO). The extension of Required Navigation Performance (RNP) in the time domain based on APS is a natural step towards the objectives of the NextGen air traffic environment. The Required Interval Management Performance (RIMP) will provide a means to assure the interval management accuracy, availability, continuity, and integrity during terminal and approach phases of flight. This can lead to a time-based interval management concept of operations. One of the benefits of a time-based RIMP is to allow enroute and terminal air traffic controllers to manage the spacing via time in seconds instead of closely monitoring merging traffic's speed and distance for maintaining safe separation and compressing the traffic flow from en-route minima [3]. With the combination of APS and RIMP (APS-RIMP), workload of Air Navigation Service Provider (ANSP) controller can be potentially reduced. RIMP compliant airplanes will also ensure the performance and accuracy in delivering airplanes at managed spacing intervals. This document will present the concept of applying RIMP in APS, describe the system components, identify key system parameters, and discuss the derivation of RIMP requirements, procedures, assumptions, and RIMP dependency of uncertainties in airplane's flying performance and equipment performance.

6.2 System Overview

The air traffic operations outlined in this document provide an APS-RIMP concept for aircraft converging to a common destination such as a runway or an intermediate navigation fix. APS is a potential speed advisory element of future high-density arrival and departure operations envisioned in the NextGen air traffic system. The focus of this APS-RIMP concept is the terminal and final approach portions of the flight. The precision spacing is accomplished by sequencing the arriving aircraft early in the initial descent phase. Each aircraft is assigned a reference aircraft to follow as shown in Figure 6. The paired aircraft may share a portion of the final assigned route, but this is not required. To achieve significant arrival density increase, this concept relies on precise spatial and temporal navigation that must be achieved for safe flight

operation. This is accomplished by extending the RNP methodology to include an interval management time performance with associated uncertainty in seconds. Similar to the lateral RNP rating, an interval management time rating will define a maximum uncertainty and a containment time which is defined in section 1.4.4 of this document.

All aircraft engaged in this APS operation must meet a certain level of RIMP. Different levels of RIMP are described in section 1.4.4 of this document. This applies to both the reference aircraft and the ownship. This concept applies to sequences of paired aircraft where the ownship itself becomes the reference aircraft for the subsequent following aircraft.

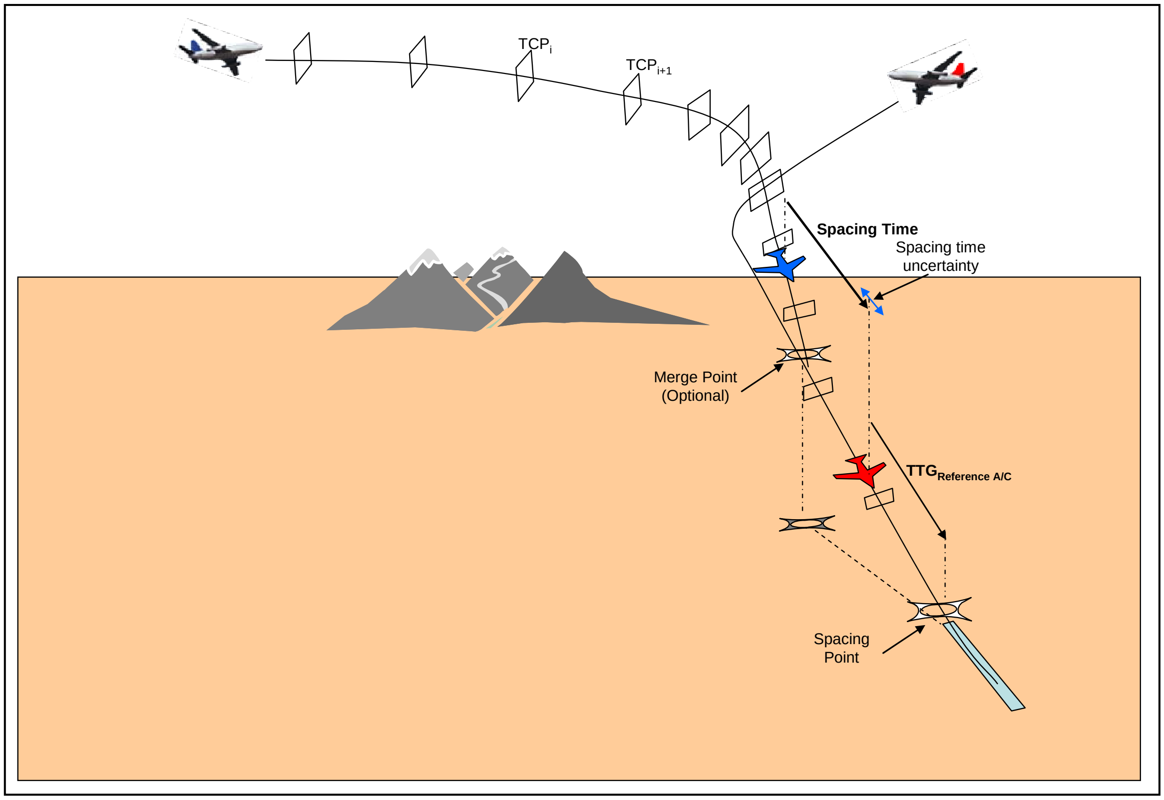

Figure 6 - Overview of APS-RIMP Operation

The APS-RIMP precision spacing concept outlined here uses many aspects of the NextGen technology to perform the required navigation and guidance. This includes integrated surveillance capabilities provided by Automated Dependent Surveillance – Broadcast (ADS-B), Traffic Information Service – Broadcast (TIS-B), Flight information Service – Broadcast (FIS-B) and associated ground radars, and precision navigation and timing provided through Global Navigation Surveillance System (GNSS). It also relies on digital data link communication with the ANSP facilities and personnel. The techniques used to accomplish the precision spacing include automatic 4 Dimension (4D) trajectory generation to the desired destination or navigation fix, real-time adjustments to the prescribed velocity profile to maintain the desired separation, and 4D navigation performance monitoring to ensure the RNP and RIMP for the precision spacing operation is available and attainable.

An integrated navigation system as addressed here includes one or more navigation sensors (such as Inertial Navigation System (INS)/Global Positioning System (GPS)), one or more air data sensors, and other relevant aircraft sensors (such as angle of attack, propulsion system sensors, etc.) to assess overall system performance, surveillance sensors (such as ADS-B), digital data link with the air traffic control authority (ANSP) and extensive processing capability to define 4D trajectories and perform the required 4D guidance (Figure 7). The navigation and guidance algorithms developed in support of this concept perform position estimation, path definition, path steering, and calculation of Time-To-Go (TTG) to the destination (navigation fix or runway threshold) for the aircraft as well as for the lead aircraft to which the ownship has been paired to follow.

The APS system will provide a precise adjustment to the nominal speed command to achieve the spacing constraint, and provide the flight crew with situation indications and alert them if the required spacing can not be achieved.

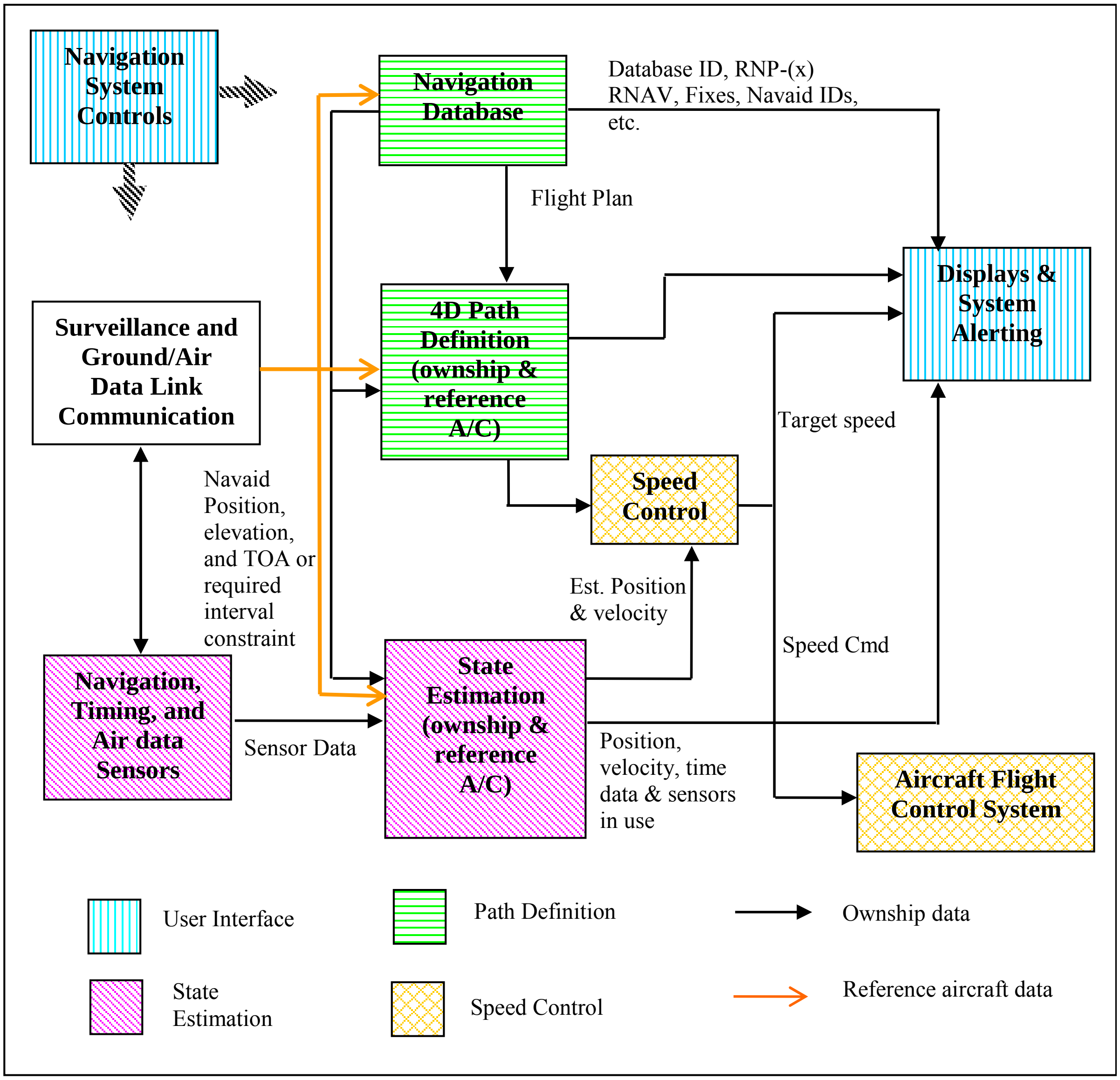

Figure 7 - APS System Block Diagram

6.2.1 State Estimation

Position estimation requirements are outlined in RTCA DO-236B (section 1.2.1) [3]. Additionally, APS-RIMP operation will require timing, surveillance, wind and air temperature information. Precise time measurement using a common time reference and an accurate estimate of time uncertainty associated with that measurement are needed to arrive at the ownship time-to-go estimates. The current position and speed of reference aircraft and its intended 4D trajectory are needed for the reference aircraft's time-to-go calculations. Finally, the predicted or measured wind field along the terminal operation and approach path is needed.

The method by which the precise timing, surveillance data, and wind and air temperature estimates are acquired is not provided here. However, this document provides overall requirements for system performance, accuracy, integrity, continuity, and availability of the data.

6.2.2 4D Path Definition

The path definition function computes the defined 3D path and associated speeds to be flown. A complete 4D path will consist of a number of straight or arc segments in the horizontal plane plus altitude and speed specifications as shown in Figure 8. Each segment ends at a trajectory change point (TCP). The TCPs are assigned by a 4D trajectory generation algorithm which attempts to optimize the spacing and merging of the ownship with the assigned reference aircraft. A TCP may overlap an existing navigation fix (Area Navigation (RNAV) waypoint, airway fix, etc.) but this is not required. It is, however, anticipated that the trajectory endpoint will coincide with a known navigation fix such as the runway threshold or final approach fix (FAF). Each generated trajectory segment or leg will include complete horizontal and vertical navigation information as well as a nominal target speed (CAS or Mach) to fly.

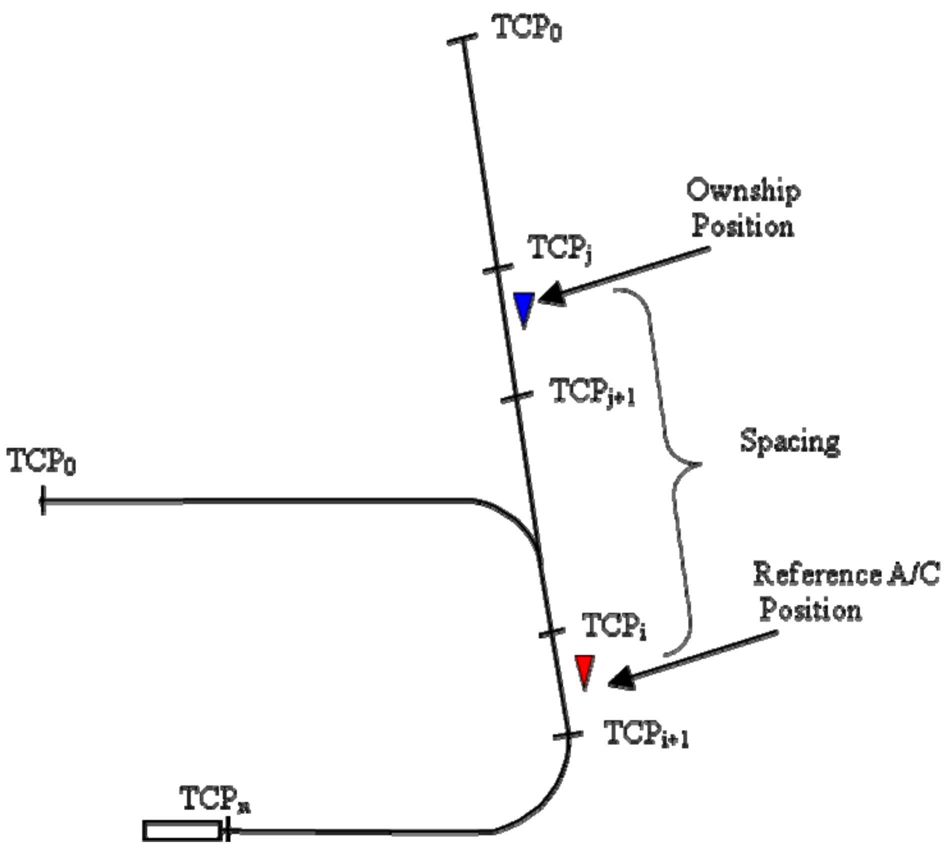

Figure 8 - Representative Layout of Paired Airplanes in Precision Spacing Mode

For each leg of the trajectory, the lateral aspects of path definition determine a geographically fixed ground track from origin to destination. This defines a 2D component of the flight path. The sub-functions involved are:

1. TCP location definition in latitude and longitude, or in the case of TCP definitions that do not have exact location information, an estimate of the TCP position based on the known or predicted state of the aircraft;
2. Leg type definition as provided in RTCA DO-236B and ARINC 424;
3. Leg transition definition which specifies turning to the next leg prior to intercepting the waypoint or flying through the waypoint prior to turning, etc.;

For each leg of the trajectory, the vertical aspect of the path definition determines an elevation change from the TCP at the beginning of the leg to the TCP at the end of the leg. This adds the 3rd dimension to the defined flight path. The vertical aspect sub-functions are:

1. Altitude or flight level constraints associated with waypoint definition; (Flight Level, corrected barometric altitude, temperature compensated altitude, or height above ellipsoid for GPS based precision approach)
2. Optional vertical angle or altitude change associated with the leg definition and vertical transition definition which specifies how the leg should be flown. For example, climb and hold or follow a glideslope;
3. Optional speed constraint;

The temporal aspects of the path definition determine the method used to satisfy time constraints associated with either the precision separation requirement or time of arrival constraint at the destination waypoint. The time constraints must take into account the lateral and vertical trajectory, the flight environment, and real-time parameters provided by the ANSP and the assigned reference aircraft. This is accomplished through speed control which controls the fourth dimension (time) for the flight path. The temporal aspect sub-functions are:

1. Nominal interval management time;
2. Optional speed constraint;

6.2.3 Speed Control

The speed control function uses the planned 4D trajectories of both the ownship and the lead aircraft along with current measured positions and velocities of both the ownship and the reference aircraft, latest wind estimates, and other associated parameters to determine the along-path range to the spacing point, speed variation, and target speed command. These parameters are used to correct errors and interval variations relative to the reference aircraft. The lateral and vertical steering functions are defined in RTCA DO-236B [3] and are omitted from this document. This document instead focuses on the speed control function.

To achieve precise arrival spacing, the navigation system must compute a number of parameters for both the ownship and the reference aircraft. These parameters include the distance along the

trajectory from the current estimated position to the interval management point (such as the runway threshold or a common merge point), estimated ground speed for each segment of the trajectory, and a total TTG to arrive at the interval management point. These calculations require knowledge of the current and predicted states of the ownship and lead aircraft, as well as external factors such as the forecast wind and temperatures along the trajectory. Prior to the start of this paired approach, the trajectory generation algorithms generate an optimum profile for both the ownship and the reference aircraft. When executed, these 4D trajectories will ensure achieving the desired interval at the interval management point, and will provide an efficient terminal area operation (with constraints such as fuel burn, noise abatement, etc.). Once the aircraft are paired, the precision spacing function computes a change in planned speed for the ownship as needed to attain the precise spacing interval upon arrival at the interval management point. The target speed will be the sum of the planned trajectory speed at the current location on the trajectory plus the required adjustment to account for variations of aircraft states of both the ownship and the reference aircraft. The target speed may be periodically updated as new navigation data and/or new constraints become available and as the estimates of the atmospheric parameters change. This target speed will be displayed to the flight crew and could also be supplied to the flight control system for possible automated speed control operations.

The accuracy of TTG prediction for interval control purposes will depend upon the accuracy of the parameters input or calculated, the control system accuracy, external factors such as winds, and the aircraft performance (including operating limits). As the reference aircraft approaches the interval management point, the accuracy of the TTG prediction will increase. The aircraft performance limitations such as speed and angle of attack limits will become the primary constraint on achieving the required spacing time without altering the flight path.

6.2.4 User Interface

6.2.4.1 Controls, Displays, and System Alerting

The user interface is achieved through system controls, displays, and alerting functions. These functions provide the means for system initialization, 4D trajectory generation and progress monitoring, active speed control and presentation of spacing time data for flight crew situational awareness. Refer to RTCA DO-236B (section 1.2.4.1) for additional information on user interfaces.

6.2.4.2 Reporting

The aircraft's instantaneous position and velocity must be reported via a digital data link (ADS-B). Depending on the required level of RIMP, other critical parameters may be required in the data link such as the planned 4D trajectory currently being flown by the aircraft.

6.3 Required Interval Management Performance

6.3.1 Time Navigation

The NextGen TBO environment is expected to include precise time-based operations where aircraft will be required to arrive at a point at a specified time. This time may be a fixed time of arrival or a time relative to the arrival time of the reference aircraft. The first type of time operation is referred to as Time of Arrival Control (TOAC), while the second is referred to as relative time spacing.

In addition to time computation and control accuracy, there is also a need to provide a level of confidence in which aircraft can perform time operations at the geographic fixes in a TBO environment.

6.3.2 RIMP Concept

The concept of time performance has not been defined by the ICAO in the same manner as RNP, and the Minimum Aviation System Performance Specification (MASPS) addresses accuracy requirements of ETA and TOAC at only a very high level. Because of the perceived importance of time-based operations in the NextGen Air Traffic Management (ATM) environment, this document develops a proposed RIMP construct and associated requirements.

For consistency with the ICAO definition of RNP, this document defines RIMP as: A statement of the time navigation performance accuracy, integrity, continuity and availability necessary for time interval management operations within a defined airspace.

6.3.3 Application of RIMP

The term RIMP is applied as a descriptor for operations that can be part of airspaces, routes, and procedures. Unlike RNP, the descriptor is only applied to each instance where RIMP is required and not the entire airspace, since interval management is done on an operation-by-operation basis. This concept, however, could eventually be applied to the entire airspace.

6.3.4 RIMP Types

The term RIMP-x-y is introduced to denote RIMP operations.

The x indicates the type of RIMP operation

A – Absolute Time
R – Relative Time (ASAS Spacing)
O – Open Loop (Time prediction only, no time control).

Note: The open loop is a place holder in anticipation of future changes to DO-236B [2]. Additional types of operations may be defined in the future as well. One such operation could be a combination of absolute time at a geographic fix with relative spacing prior to the fix.

The y indicates the limit of RIMP accuracy in seconds (e.g. RIMP-A-10 indicates absolute time control with 10 seconds required accuracy). There is a correlation between the type and accuracy where the Open Loop type can only achieve a low accuracy. The RIMP accuracy for open loop is expressed in % of TTG as it is expected to only be used for pairings where ownship and the reference aircraft are further out.

6.4 Assumptions

The APS concept of operations relies on the premise that by knowing both the ownship and the reference aircraft's 4D trajectories and the aircraft position along that 4D trajectory, it is possible to determine the ownship and the reference aircraft's Time-To-Go to a given point on their individual trajectories. Therefore, it is necessary to define a means of acquiring the aircraft planned trajectory and position on that trajectory, and define an assumptions-based predictive model for the computation of a 4D trajectory and Time-To-Go.

6.4.1 Reference Aircraft State

The RIMP concept assumes that all aircraft in the airspace continuously transmit and receive ADS-B data in compliance with RTCA DO-242A including the following parameters:

- Target identity
- Latitude and longitude
- Pressure altitude
- Position accuracy and integrity
- North and east velocity
- Vertical speed
- Velocity accuracy and integrity
- Time of applicability (reference time of the other state parameters)

It is further assumed that ownship and reference are either using the same transmission format for ADS-B (e.g. 1090ES or UAT) or the airspace is served by an Automatic Dependent Surveillance – Rebroadcast (ADS-R) service that reliably echoes messages between the two transmission formats with negligible delay.

6.4.2 Ownship State

The spacing function has access to at least the set of ownship state parameters that is available via ADS-B for the reference aircraft.

6.4.3 Reference Aircraft Intent

The APS concept assumes that the aircraft has knowledge of the reference aircraft lateral, vertical, and speed profile. There are many possible mechanisms for acquiring an aircraft trajectory ranging from assuming that the reference aircraft will adhere to a published augmented Standard Terminal Arrival Route (STAR) with the augmentation in the form of altitude or speed

crossing restrictions at waypoints on the route, to the acquisition in real time of a Flight Management System (FMS) profile being broadcast by the reference aircraft. The method used is a determinant factor in quantifying the level of accuracy and integrity of the trajectory.

Regardless of the method used, the RIMP level of performance will be a function of:

1. The errors and uncertainty in the reference aircraft actual lateral, vertical and speed profile flown versus its published profile. The Reference aircraft is assumed to be RNP compliant in that its lateral and vertical deviation from the published profile is bounded by the profile's published RNP accuracy and integrity figures of merit.
2. The errors and uncertainties in the true wind field and temperature profile versus the forecast. It is assumed that ownship has access to a forecast wind field and temperature profile applicable to both the ownship and the reference aircraft.

6.4.4 Ownship Intent

The RIMP concept assumes access to detailed and accurate ownship intent information and associated accuracy metrics from the onboard FMS or an equivalent system. Ownship is assumed to be operating at a specified RNP level.

6.5 Definitions

This section defines key terms that are used throughout this document.

6.5.1 Required Interval Management Performance

REQUIRED INTERVAL MANAGEMENT PERFORMANCE (RIMP)
A statement of the performance accuracy of an in-trail paired interval management operation between two aircraft.

PAIRED INTERVAL MANAGEMENT
An operation where a trailing aircraft is required to arrive at a *waypoint* a specified time period after a specified reference aircraft arrives at that same *waypoint*.

OWNSHIP
The trailing aircraft which is controlling the interval in a *paired interval management* operation.

REFERENCE AIRCRAFT
The leading aircraft which *Ownship* is required to space relative to.

6.5.2 Trajectory

3D POSITION
A position in space consisting of latitude, longitude, and altitude.

WAYPOINT
A predetermined geographical position used for route definition and/or progress reporting purposes that is defined by latitude and longitude [2].

TIME REFERENCE
The reference time source for the trajectory; for example, Universal Coordinated Time (UTC).

CURRENT TIME
The present time according to the *time reference*.

PREDICTED TRAJECTORY
The predicted *3D position* of an aircraft as a function of time.

ESTIMATED TIME
The time input to the trajectory prediction function, synchronized to the *time reference*.

ESTIMATED TIME OF ARRIVAL (ETA)
The time at which an aircraft will arrive at a defined point on the *predicted trajectory*.

ESTIMATED TIME TO GO (ETTG)
The predicted duration from the *current time* until the aircraft reaches a defined point.

TIME TO GO (TTG)
The duration from the *current time* until the aircraft reaches a defined point, typically in this discussion, the *Interval Management Point*.

TRAJECTORY CHANGE POINT (TCP)
A discrete point on the *predicted trajectory* containing the latitude, longitude, altitude, time, and speed (either CAS or Mach). This is a basic set of variables that may be standardized and/or expanded in the future.

INTERVAL MANAGEMENT POINT
A defined *waypoint* on the *predicted trajectory* at which the specified interval between ownship and the reference aircraft is defined.

6.5.3 Error Terms

6.5.3.1 Along-Track

This document considers only along-track error. Cross-Track and Vertical errors are considered only as they contribute to the along track error. Figure 9 below summarizes these terms.

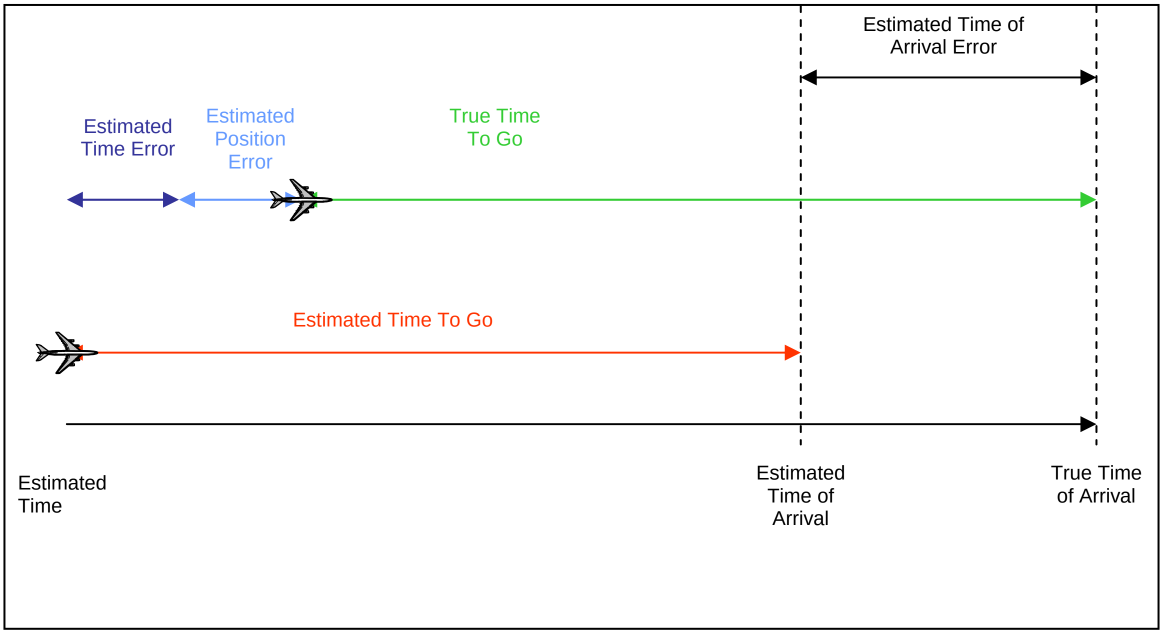

Figure 9 - Along Track Components of Navigation Error Terms

ESTIMATED TIME ERROR (ETE)
The difference between the *current time* and the *estimated time*, synchronized to the *time reference*.

ESTIMATED POSITION ERROR (EPE)
The arrival time error due to difference between the true position and the *estimated position* along the current heading of the aircraft, expressed in seconds.

TIME TO GO ERROR (TTGE)
The difference between the true time to go and the *estimated time to go*.

ESTIMATED TIME OF ARRIVAL ERROR (ETAE)
The difference between the true time of arrival and the *estimated time of arrival* at a point. This is equal to the vector sum of the *estimated time error, estimated position error,* and *time to go error.*

6.5.3.2 Interval Management Performance

There are errors associated with a paired interval management operation which must be considered in the Required Interval Management Performance.

DESIRED SPACING
The required time interval, in seconds, between Ownship and Reference Aircraft at the Interval Management Point as might be contained in an instruction issued by the ANSP or defined in a procedure.

DEFINED SPACING
The time interval, in seconds, between Ownship and Reference Aircraft at the Interval Management Point that is input to the spacing computation function.

ESTIMATED SPACING
The output of the spacing computation function, equal to the difference between Reference Aircraft's *estimated time of arrival* and ownship's *estimated time of arrival* at the *interval management point*. This does not take into account potential future speed changes prior to the *interval management point* that are not reflected in the *predicted trajectory.*

ESTIMATED TIME BIAS (ETB)
The portion of the *estimated time of arrival error* that will be identical between ownship and reference aircraft (for example due to a shared wind error along a common path segment).

SPACING DEFINITION ERROR (SDE)
The difference between the *desired spacing* and the *defined spacing*, for example due to a difference in resolution between the spacing input and the necessary spacing.[16]

COMPUTED SPACING ERROR (CSE)
The difference between the *estimated spacing* and the *defined spacing*.

SPACING ESTIMATION ERROR (SEE)
The error in the computation of *estimated spacing.* This is equal to the sum of the *estimated time of arrival error* for both ownship and reference aircraft minus any *estimated time bias*.

SPACING CONTROL AUTHORITY (SCA)
The ability of ownship to maneuver in order to compensate for *computed spacing error* and *spacing estimate error.*

TOTAL SPACING ERROR (TSE)
The difference between the true spacing and the *desired spacing*. Until ownship has reached the *interval management point*, TSE can only be estimated based on a prediction of owship *time to go*, either reference *time to go* or measurement of reference *IMP* crossing time, and estimated *spacing control authority*. It is equal to the sum of the *spacing definition error, computed spacing error,* and *spacing estimation error* less the *spacing control authority*. The *spacing control authority* is subtracted because it represents a controllable portion of the error. The uncontrollable portion of the error is analogous to the Flight Technical Error (FTE) in RNP.

Since the *spacing estimation error* has to rely on a probabilistic prediction, there may be a need for future control actions to correct for "true" disturbances and errors that were not part of the prediction. Figure 10 also shows how the uncertainty of the predicted time grows the farther from ownship the spacing point is located.

[16] For example, if the desired spacing specified by ATC is in seconds but the defined spacing that is input into the system can only be in tenths of minutes, there could be up to a 3 second spacing definition error.

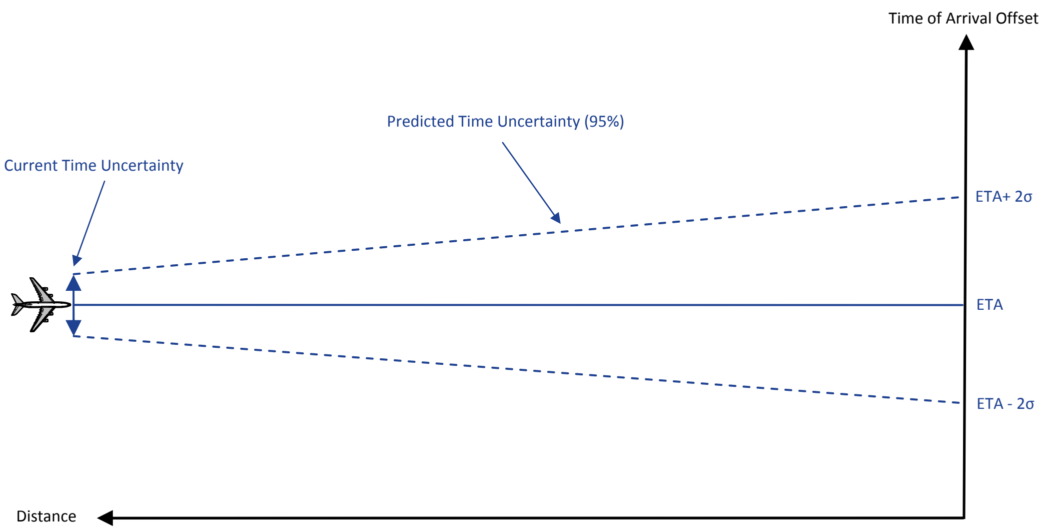

Figure 10 - Reference Time Profile with Uncertainty

6.5.3.3 Along Track Containment Concept

The concept of along-track containment must be coupled with the concept of lateral (or cross-track) containment as defined in RTCA DO-236B. If a desired lateral path exists, the Cross-Track Containment Limit combined with the Along-Track Containment Limit defines a region around the desired location of the aircraft at a defined future time T. The probability that the aircraft will be within that region in both the cross-track and along-track domains at time T, can be bounded. This time T may be a fixed time, or it may be an offset time relative to another aircraft's ETA. This concept is depicted in Figure 11 below, and the definitions of these terms follow.

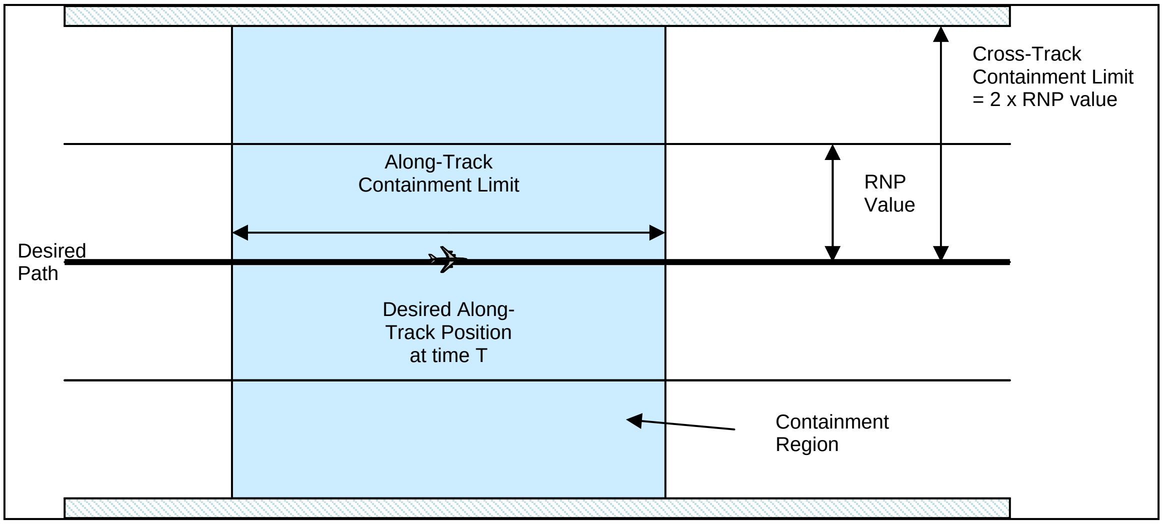

Figure 11 - Along-Track and Cross-Track Containment Region

Along-Track **containment integrity** requirements limit the probability of the Total Spacing Error exceeding the Along-Track Performance requirements with no annunciation at least some specified time before the defined time T.

Along-Track **containment continuity** requirements limit the probability of a loss of function. In this context, function is defined as the ability of the APS system to meet the along track containment requirement (i.e. to be within the desired containment limit at time T).

There are five possible system states relative to along-track containment limit, C. These states are:

6) S1: TSE Error > C, TTG > ΔT, no alert (Integrity)
7) S2: TSE Error > C, TTG > ΔT, alert (Continuity)
8) S3: TSE Error > C, TTG < ΔT, no alert (Integrity)
9) S4: TSE Error > C, TTG < ΔT, alert (Continuity)
10) S5: TSE Error < C, no alert (Normal Operations)

Note: P(S1) + P(S2) + P(S3) + P(S4) + P(S5) = 1 where P(x) is the probability of the system being in State x.

ΔT is the minimum amount of time prior to reaching the Interval Management Point that the alert must be made if the aircraft cannot achieve the required spacing time.

States 1 and 3 represent the set of events associated with a loss of along-track performance with no annunciation (alert), and are thus the **integrity requirements**. The uncertainties associated with time predictions generally increase with distance from the current trajectory point (primarily due to forecast wind uncertainties). Therefore, the probability that the along-track performance cannot be achieved will generally decrease with distance to the Interval Management Point. Thus, the probability of State 1 will be greater than the probability of State 3 (P(S1) >> P(S3)) due to TTG being > ΔT. However, it also needs to be considered that the control authority that

ownship has to correct for these uncertainties will also generally decrease as the aircraft approaches the Interval Management Point. This needs to be considered when determining a time T beyond which it is critical that an annunciation be received. Thus, the probability of S1 must be less than XX[17] per flight hour, while the probability of S3 must be less than YY per operation.

The **continuity requirement** applies to states S2 and S4 where the loss of function is detected and annunciated. When current time is still far before T (TTG > ΔT), the available control authority will be larger, and thus the probability of state S2 must be less than WW per flight hour. When the aircraft is close to time T the control authority is greatly reduced, and thus the probability of S4 must be less than ZZ per flight hour. S5 represents the normal operation where the error is less than the containment limit.

In addition to the containment requirements, there is an **uncertainty parameter** associated with the predicted ETA at various points on the predicted trajectory. This uncertainty must be bounded to ensure appropriate control authority is available.

CONTAINMENT
A set of interrelated parameters used to define the performance of a time control system. These parameters are *containment integrity, containment continuity,* and *containment region.*

CONTAINMENT INTEGRITY
A measure of confidence in the estimate, expressed as the probability that the system will detect and annunciate the condition where the TSE is greater than the along-track containment limit and the condition has not been detected.

CONTAINMENT CONTINUITY
The capability of the total system to satisfy the performance limit without nonscheduled interruptions during the intended operation. Nonscheduled interruption is defined to be either 1) total loss of time prediction capability; 2) a failure of the system which is annunciated as a loss of time performance capability; or 3) a false annunciation of loss of time performance capability.

CONTAINMENT REGION
A region in both the along-track and cross-track dimensions, centered on the *desired along track position* on the *desired path* at a desired time T, to which the *containment integrity* and *containment continuity* are referenced.

CROSS-TRACK CONTAINMENT LIMIT
As defined in DO-236B MASPS.

[17] This and the following probability parameters will need to be determined based on a TLS and any mitigations that are identified as part of the procedures defined by the ANSP. In practice, they will likely be tailored to specific RIMP performance categories.

ALONG-TRACK CONTAINMENT LIMIT
A time that defines the one-dimensional containment limit in the along-track dimension. The resulting *containment region* is centered on desired along-track position at desired time T and is bounded by +/- the along-track containment limit in the along-track dimension.

ESTIMATED TIME OF ARRIVAL UNCERTAINTY
A measure based on a defined scale in seconds which conveys the performance of the estimated time of arrival at the center of that containment region.

This measure is required because a type of integrity performance measure is needed. It is based on a defined scale (e.g. 95%).

The containment region is bound around ETA where the actual time of arrival will be within the ETA uncertainty in seconds.

The RNP-equivalent for the ETA uncertainty is the Estimated Position Uncertainty.

6.6 System Performance Requirements

6.6.1 Accuracy

A measure of the difference between an aircraft's reported planned interval, i.e. ADS-B report, as compared to its achieved interval. It is given by a number bounded by a confidence value. For example; within the RIMP-R-10 interval management operation the Total Spacing Error cannot be greater than 10.0 seconds 95% of the time.

6.6.2 Integrity

The probability that information provided by a system will not be hazardously misleading. It is generally a number, per operating hour, which expresses likelihood that a system will send the user bad/incorrect information that could cause a potentially dangerous situation without a timely warning. For example; the likelihood that a Total Spacing Error exceeds a maximum of 10.0 seconds containment, without detection, shall be less than 10^{-5} per flight hour.

6.6.3 Continuity

The capability of a total system to perform its intended function without a non-scheduled interruption during the intended operation assuming the system was available when the procedure was initiated. Continuity is expressed per unit of time. For example; the calculations of a single thread transponder mean time to failure of 5,000 hours.

6.6.4 Availability

The probability that a system will perform its required function at the initiation of the intended operation. For example; the FAA target for availability of the Wide Area Augmentation System is 0.999.

7 Conclusions

7.1 Observations

From the outset, this effort planned to use the existing RNP concept as a baseline for extending the construct to encompass several operations involving constraints that are not fixed relative to the Earth's surface ('static' RNP) but rather are relative to the position of other aircraft ('dynamic' RNP). Basing these dynamic RNP constructs on the existing RNP formulation provided a useful starting point and encouraged casting the problems in generally recognized terms, such as TLS and containment.

An attempt was made to follow the RNP MASPS as a template to document these concepts. The MASPS document outline was adequate for capturing, explaining, and organizing requirements, but it was not well suited to the task of providing a clear description and analysis of new and unfamiliar air traffic management concepts. Initially, the study team sought a unified construct capable of encompassing a wide range of multi-vehicle operations, but the team was unable to formulate such a generic construct for defining containment and integrity without defining the nature of the operation. Therefore, the study was refocused on two specific types of two-vehicle operation: RSSP and RIMP.

The extension of the static RNP construct to the 4D dynamic operations described in the preceeding sections uncovered a number of complications. The first difficulty was the lack of well developed existing constructs for vertical and longitudinal RNP. Though the existing RNP standards include vertical and longitudinal performance measures, they do not contain fully developed constructs for containment and integrity as has been developed for the lateral case. At a minimum, the longitudinal construct was required for both operations examined in this work. To complete the RSSP construct, a detailed vertical construct will be required. While extending the lateral containment and integrity constructs to the longitudinal dimension was difficult, the issues associated with defining a performance standard based on the interaction of two independent vehicles further compounded the problem. Finally, extending the analysis beyond the present state of the vehicle to encompass key metrics that exist only as predicted future quantities added another layer of complexity. Trying to properly account for external (not intrinsic to the aircraft system) error sources, such as the impact of unquantified wind prediction/estimation errors on trajectory predictions, proved particularly elusive.

Trying to define generic constructs not coupled to a specific set of procedures and algorithms led to unresolved issues for both constructs examined. Some aspects of the self-separation performance were found to depend on how and when trajectory adjustments are made (e.g. a few discrete maneuvers vs. continuous adjustment). Similarly for the spacing problem, the spacing

performance was found to likely depend on the tuning of the speed adjustment algorithm (e.g., whether predicted errors are nulled early or late; whether speed changes are continuous or discrete). Issues also arose as to how mixed-equipage operations would be addressed in a performance standard, as well as transitions into and out of self-separation and interval-management operations.

7.2 Next Steps

Before the level of safety can be analyzed for either type of operation, each construct needs to have a detailed ConOps developed. The ConOps would include procedures, operational constraints, and mitigation strategies for non-normal conditions.

The complete RSSP concept needs to address the vertical dimension. The containment construct for RSSP should capture the nonlinearities of the problem and address non-circular exclusion zones. The safety case for RSSP will require a much deeper understanding of the impact of traffic density/complexity and trajectory predictability and stability on the achieved level of safety. Extensive Monte Carlo testing will be required to generate a quantatative understanding of these factors. Extension of RSSP concepts to constraints other than air vehicles (e.g. weather cells, prohibited airspace, volcanic ash clouds, etc.) is expected to be relatively straightforward.

For the RIMP construct, one or more representative interval management algorithms (including both ETA prediction and speed profile management) need to be employed to permit quantatative analysis of performance. The authors have determined that such analysis can only be performed using simulation-based techniques. A basic capability has been constructed using a simple interval control algorithm. Further development by this team will refine the control algorithm and allow for introducing wind, sensor, time-to-go prediction, and aircraft performance model errors into that algorithm. This version of the RIMP simulation model will also be capable of supporting Monte Carlo simulation studies. The model should eventually be extended to permit simulation of sequences of self-spacing aircraft so that the dynamics of the chain using various proposed interval control algorithms may be studied.

References

1. Barmore, Bryan E., Abbott, T.S., Capron, W.R., and Baxley, B.T.: "Results for Airborne Precision Spacing along Continuous Descent Arrivals," AIAA ATIO 2008.
2. Joint Planning and Development Office: "Concept of Operation for the Next Generation Air Transportation System", Version 2.0, 13 June 2007
3. RTCA DO-236B: "Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation" RTCA, Incorporated
4. Hull, James, Barmore, B., and Abbott, T.: "Technology-Enabled Airborne Spacing and Merging," IEEE 2004.
5. Abbott, T.S.: "A Trajectory Algorithm to Support En Route and Terminal Area Self-Spacing Concepts," NASA/CR-2007-214899.

Acronyms

4D	4 Dimensional
A/C	Aircraft
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-R	Automatic Dependent Surveillance - Rebroadcast
ANSP	Air Navigation Service Provider
APS	Airborne Precision Spacing
ASAS	Airborne Separation Asssurance/Assistance System
ATM	Air Traffic Management
ATS	Air Traffic Services
CAS	Calibrated Air Speed
CNS	Communication, Navigation, Surveillance
ConOps	Concept of Operations
CSE	Computed Spacing Error
DOF	Degrees Of Freedom
EPE	Estimated Position Error
ETA	Estimated Time of Arrival
ETAE	Estimated Time Of Arrival Error
ETB	Estimated Time Bias
ETE	Estimated Time Error
ETTG	Estimated Time To Go
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FIS-B	Flight Information Service - Broadcast
FMS	Flight Management System
FTE	Flight Technical Error
GNSS	Global Navigation Surveillance System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
INS	Inertial Navigation System
JPDO	Joint Planning and Development Office
MASPS	Minimum Aviation System Performance Standards
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
PCA	Point of Closest Approach
RIMP	Required Interval Management Performance
RNAV	Area Navigation
RNP	Required Navigation Performance
RSSP	Required Self Separation Performance
RTCA	Radio Technical Commission for Aeronautics
SBL	Separation Boundary Lateral
SBV	Separation Boundary Vertical
SCA	Spacing Control Authority
SDE	Spacing Definition Error

SEE	Spacing Estimation Error
SM	Separation Management
STAR	Standard Terminal Arrival Route
TBO	Trajectory Based Operation
TCP	Trajectory Change Point
TIS-B	Traffic Information Service - Broadcast
TLS	Target Level of Safety
TOAC	Time Of Arrival Control
TSE	Total Spacing Error
TTG	Time To Go
TTGE	Time To Go Error
UAT	Universal Access Transceiver
UTC	Universal Coordinated Time
VNAV	Vertical Navigation

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14. ABSTRACT
This Annual Interim Report summarizes the activities led by Raytheon, in collaboration with GE Aviation and SAIC, and presents the results obtained during the first year of this research effort to expand the RNP concept to 4 dimensions relative to a dynamic frame of reference.

15. SUBJECT TERMS
RNP; Interval management; Performance based operations; Self-separation

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